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Granite magma generation, ascent and emplacement within a transpressional orogen

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Crustal thickening during transpressive orogenesis may produce anatectic granites which may then localize deformation leading to transcurrent movement. Granites may be transported from sites of generation through the mid-crust in dyke-like channelways within relatively narrow strike-slip shear zones which link to major fault zones in the upper crust. Extensional jogs within fault systems provide developing sites for the assembly of plutons from magma arriving from below. The model is based upon observations from the Cadomian belt of NW France which exposes sections through middle and upper levels of the late Precambrian crust within different elements of the orogen. The mechanism provides a favourable alternative to diapirism, and explains the common collocation of granites and shear zone/fault systems within orogenic belts.

Growing realization that diapirism is not the dominant process by which granite magmas ascend through the crust (e.g. Bateman 1984) requires investigation of alternative mechanisms. Valuable insights may be gained from studies of granitic magmatism in transpressive settings. Transpression will thicken the crust and structurally invert sedimentary basins, which may lead to high-temperature metamorphism and anatexis. The common collocation within transpressional orogens of granitic rocks with crustal-scale strike-slip shear zones and faults (e.g. Hutton 1988; Hutton & Reavy 1992) implies that such tectonic features may act as fundamental controls on the ascent and emplacement of magmas. The St Malo and Mancellian regions of NW France expose middle and upper crustal sections within the late Precambrian, Cadomian orogenic belt and display granitic rocks intimately associated with shear zones and fault systems. We integrate previously published and newly acquired field, geochemical and isotopic data to derive a generalized model for the ascent and emplacement of granite magma within a transpressional orogen.

Geological setting. The late Precambrian, Cadomian belt of NW France (Fig. 1) records subduction-related orogenic activity which culminated in the accretion of magmatic arc and marginal basin terranes along a continental margin above a south-dipping subduction zone (D'Lemos *et al.* 1990 and references therein). In northern Brittany, steep, sinistral strike-slip shear zones and associated structures are interpreted to have formed during regional (polyphase) transpression in an oblique convergent setting (Treloar & Strachan 1990, but see also Brun 1992 and reply). The Fresnaye shear zone (Fig. 1) separates arc-related terranes to the NW from behind-arc terranes to the southeast. Arc-related terranes are characterized by abundant *c.* 700–570 Ma calc-alkaline plutonism intrusive into mid-Proterozoic basement (Trégor–La Hague region) and Brioverian supracrustal sequences (St Brieuc region; Fig. 1). In contrast, the St Malo and Mancellian regions to the southeast (Fig. 1) expose intracrustally generated granitic rocks formed at *c.* 550–540 Ma (Graviou & Auvray 1985; Brown & D'Lemos 1991). The St Malo region exposes heterogeneously folded and mylonitized migmatites and anatectic granites (Brown 1979) tectonically interleaved with medium-grade Brioverian metasediments. The Mancellian region mainly exposes variably deformed greenschist to sub-greenschist facies Brioverian metasediments intruded by undeformed granitic plutons.

Cadomian structures within the St Malo and Mancellian regions are represented in Brioverian rocks by NE- to E-trending, upright folds and associated schistosity or cleavage. Folds throughout the region plunge gently to moderately NE or E while the regional metamorphic grade decreases eastwards. The Mancellian granites locally contain miarolitic cavities and develop well-defined contact aureoles. These features imply that the deepest structural levels are represented by the St Malo area in the west with shallower levels to the east. Cadomian strain in the St Malo area is heterogeneously distributed, and concentrated into subvertical, transitional amphibolite–greenschist facies ductile shear zones characterized by blastomylonitic fabrics, NE-plunging (mean 10–15°) stretching lineations and sinistral shear criteria (Brown 1978; Brun & Balé 1990; Treloar & Strachan 1990). Moderately dipping reverse shear zones in the Rance Valley may have formed as a result of strain partitioning during regional sinistral transpression (Treloar & Strachan 1990). Juxtaposition of contrasting crustal levels is thought to have resulted from sinistrally oblique (W-side up) displacement parallel to the regional stretching lineation. Even moderate amounts of cumulative regional displacement across shear zones of *c.* 40–60 km would result in a *c.* 10 km difference in crustal level across the region while Variscan fault reactivation may also account for further relative movement.

Although Strachan *et al.* (1989) assigned the rocks of the St Malo and Mancellian regions to separate tectonic units, an increasing body of geochemical and isotopic data suggests that granitoid magmatism in the two regions is genetically related (Brown & D'Lemos 1991). We therefore interpret the St Malo and Mancellian regions as different crustal levels of essentially the *same* tectonic unit. The unmetamorphosed and only weakly deformed nature of Lower Palaeozoic sediments which overlie unconformably components of the belt testify to the limited Variscan reworking in this part of the Cadomian orogen. The present major fault pattern is interpreted to result from limited dextral Variscan reactivation of Cadomian shear zones and faults. Hence, although faulting and locally limited exposure do not allow examination of a *complete* mid- to upper crustal section, geological relationships within and between the St Malo and Mancellian regions are largely preserved intact, presenting an opportunity to study granite/host rock relationships at different crustal levels.

Granite magma genesis. In the Rance Valley (Fig. 1) greenschist facies Brioverian metasediments pass transitionally into upper amphibolite facies stromatic migmatites (metatexite) produced by low to moderate degrees of partial melting (Brown 1978, 1979; Brun & Martin 1978). With greater partial melting the stromatic structure becomes progressively disrupted, and schlieric and nebulitic migmatites (diatexites) result. Homogenized anatectic granites are locally common and result from the most advanced stage of melting, partial separation of melt from restite and convective overturning (Brown 1979). These magmas ponded and were emplaced through a less melted, though ductile, envelope of diatexite and meta-

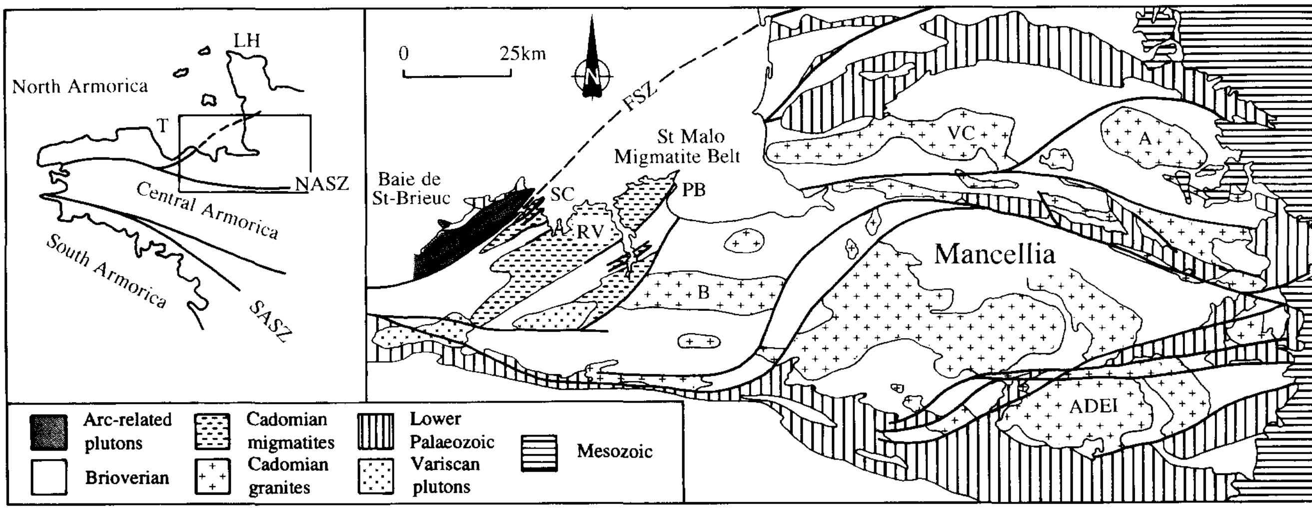

Fig. 1 Generalized geological map of the northeastern part of the Armorican Massif (see inset for location). Heavy lines represent Cadomian strike-slip shear zones (St Malo region) or younger brittle faults thought to lie along Cadomian strike-slip shear zones (Mancellia). SC, St Cast; PB, Port Briac; RV, Rance Valley; B, Bonnemain; VC, Vires–Carolles; A, Athis; ADEI, Alexain–Deux–Evailles–Ize; T, Trégor; LH, La Hague; FSZ, Fresnaye shear zone; NASZ, North Armorican shear zone; SASZ, South Armorican shear zone.

texite as both decimetric veins and diapiric bodies up to several kilometres in extent.

PT estimates of 3–8 kbar and 650–750 °C based on mineral reactions within the migmatites (Brown 1979) place melting at intermediate crustal levels (*c.* 10–20 km). Although there is some field evidence for interaction between basic and granitic magmas, geochemical, geophysical and isotopic evidence (Brown & D'Lemos 1991 and unpublished data) argue that the volume of basic magma was small and hence melting was apparently not due to the emplacement of basic magma into the crust. Polydeformed enclaves of metasediments within the migmatites indicate that the Brioverian sequence was initially deformed prior to anatexis, most probably during the *c.* 590–570 Ma tectonothermal event recorded in the Baie de St Brieuc to the west (Guerrot & Peucat 1990; Dallmeyer *et al.* 1991). Treloar & Brown (1990) have shown that moderate overthickening of sedimentary basins during inversion will lead to high-temperature metamorphism at mid-to-lower crustal depths for reasonable values of mantle heat flux, thermal conductivity and heat production. Experiments on natural rock compositions (Le Breton & Thompson 1988) and the results of thermal models (De Yoreo *et al.* 1989) indicate significant volumes of crustal melt can be generated through crustal thickening. Indeed, significant amounts of melt are generated for overthickening as small as 10–15 km (see De Yoreo *et al.* 1989) and De Yoreo (1988) has shown that partially molten (> 0.3 melt fraction) sections of crust substantially thicker than 1 km will be generated in less than 40 Ma. In the St Malo region, initial deformation at *c.* 590–570 Ma is considered to have resulted in structural inversion of the Brioverian sedimentary basin and high-temperature metamorphism which culminated in anatexis at *c.* 550–540 Ma.

The Mancellian granites (*s.l.*) to the east comprise mainly biotite granodiorites with small biotite schlieren and minor cordierite and muscovite and locally tourmaline leucogranite. Minor basic complexes occur in close proximity to granites in the southern part of the region, although the temporal relationship between these bodies and the granites is unclear. Common dark-grey, quartz- and biotite-rich enclaves which exhibit granoblastic textures are interpreted as restite and country rock remnants. Small garnet–cordierite enclaves within the Athis granite (Fig. 1) suggest derivation, at least in part, by dehydration melting involving biotite (cf. Le Breton & Thompson 1988). Subordinate dark, intermediate to basic, rounded enclaves which exhibit microgranitoid textures and contain plagioclase phenocrysts are considered to have a mixed-magma origin.

The Mancellian granites and anatectic granites within the St Malo migmatites exhibit a number of similarities summarized by Brown & D'Lemos (1991). Given the similar age, regional setting, petrographic, geochemical and isotopic characteristics of the two suites, Brown & D'Lemos (1991) concluded that they are genetically related, the Mancellian granites being larger volumes of homogenized magma represented by the anatectic granites of the St Malo area.

Relative timing of deformation and granite magmatism. Metatexites and diatexites within sinistral shear zones in the St Malo region show clear evidence for pervasive crystal plastic strain, demonstrating that shearing outlasted solidification. However, a number of features imply that shearing was broadly synchronous with the emplacement of anatectic granites. At St Cast and Port Briac (Fig. 1) there is a close spatial association of sinistral shear zones and dyke-like bodies, several hundreds of metres to 1 km across, of anatectic granite and leucogranite. The granites display homogeneous grain-scale C–S fabrics which contrast with heterogeneous decimetric shear zones developed in adjacent country rocks, features consistent with deformation of syn-tectonic intrusions (Gapais & Balé 1990). The variation in deformation state of associated granitic veinlets within the country rocks, which range from concordant and thoroughly mylonitized to discordant and only weakly deformed, further implies a continuum of deformation and granite emplacement. Similar relationships are observed along the Rance Valley and in nearby quarries (Fig. 1). Several *c.* 1 km-wide SW–NE-trending variably mylonitic granite bodies are interleaved with heterogeneously deformed migmatitic and metasedimentary host rocks. Pre-, syn- and post-kinematic cordierite porphyroblasts are present in mylonitic metasediments adjacent to granite contacts. Relatively undeformed granite within parts of certain shear zones is taken to show that either magma emplacement outlasted ductile shearing, or the presence of too great a melt fraction at the time of shearing to record deformation.

In contrast, granites within the structurally higher levels represented by the Mancellian region appear to have been emplaced post-tectonically with respect to deformation in the greenschist to sub-greenschist Brioverian country rocks. The granites are mainly undeformed (although weak pre-full crystallization fabrics are locally present), discordant to mesoscopic folds, and develop discrete contact metamorphic aureoles which overprint the regional cleavage.

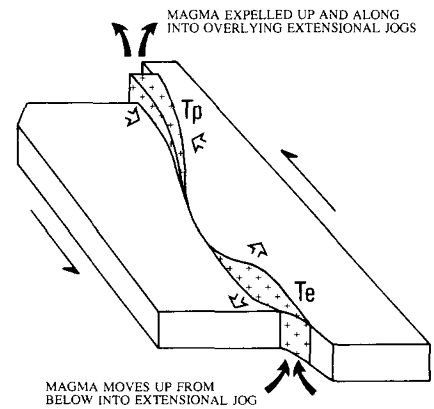

Fig. 2 Cartoon depicting a general mechanism for the upward transport of magma within an evolving sigmoidal, strike-slip shear zone or fault, showing movement of magma (black arrows) *into* a zone of transtension (Te) and *from* a zone of transpression (Tp).

Mechanisms for granite magma migration and ascent. Given our interpretation that anatectic granites were emplaced syntectonically along strike-slip shear zones in the St Malo area, we suggest that granites were transported from their site of generation through the mid-crust to their final site of emplacement up and along 'megadyke' channelways within shear zones. Migration and ascent of magma was driven by alternating dilation and compression within the anastomosing shear zone system. Magma entered ductile extensional jogs within shear zones from the underlying anatectic zone, and was expelled to other (extensional) parts of the shear zones during subsequent compression (Fig. 2), upward movement being aided by the buoyant nature of the magma. Thermal softening of country rocks during continued magma migration is likely to have enhanced ductile deformation, while the presence of magma would itself have localized deformation into the shear zones. Cordierite in proximity to shear zones is attributed to contact metamorphism driven by advected heat during granite ascent. Extensive cordierite development in some areas is seemingly inconsistent with the only limited amount of granite present within adjacent shear zones, which implies that large volumes of granite (no longer present) have been fluxed through the shear zones.

Emplacement of granite magmas. Mid-crustal, ductile strike-slip shear zones will pass upwards into linked brittle strike-slip fault systems similar to those observed along present-day oblique convergent plate boundaries. Granite magma which is transferred upwards through the crust via mid-crustal shear zones probably will be emplaced finally in extensional jogs in brittle fault systems in the upper crust. We examine this proposal further with reference to the Mancellian granites. These display considerable variation in exposed two-dimensional form (Fig. 1). The markedly linear, E–W trend of the Bonnemain and Vire–Carolles granites (Fig. 1) strongly implies a tectonic control on emplacement. The granites at higher structural levels to the east, such the Alexain–Deux–Evailles–Izé body, have much more irregular map patterns. Geophysical evidence (J. L. Vigneresse, pers. comm. 1991) suggests that the granites do not extend deeper than *c*. 5 km, and have steeply inward dipping contacts. The Mancellian granites thus apparently have the form of elongate mushrooms with relatively narrow, steeply-bounded E–W trending keels which open out upwards.

The intrusions exhibit abundant evidence for passive emplacement into brittle-deforming upper crust. Granite-country rock contacts are discordant and sharp, and show clear evidence for stoping. Locally derived (stoped) Brioverian xenoliths are common, and particularly abundant towards the E (e.g. Athis granite), indicating that stoping was more common at higher structural levels. We consider the stoping to be simply a local intrusive effect and not the main mechanism by which space was generated for granite emplacement. Dilational granite dykes provide further evidence for host extension during emplacement while the absence of strong internal fabrics within the Mancellian granites is also consistent with passive as opposed to forceful emplacement. We thus regard the granite contacts as essentially following the former sites of faults which have been modified and obscured by local intrusion effects. It is a reasonable inference that the shear zones of the St Malo area and the elongate Bonnemain and Vire–Carolles granites together define the trace of a sigmoidal and anastomosing linked strike-slip shear zone/fault system which has acted as a fundamental control on the migration, ascent and emplacement of granite magmas.

Discussion and conclusions. On the basis of our observations within the Cadomian belt of NW France we propose a simple model to account for the generation, ascent and final emplacement of granite magma within a transpressional orogen, and to explain the collocation of granites and shear zones (Fig. 3). Oblique collision of outboard arc-related terranes at the late Precambrian continental margin (*c*. 590–570 Ma) resulted in transpressive thickening of the juvenile supracrustal pile in the behind-arc terranes and fluid present anatexis *c*. 550–540 Ma. A crustal scale linked strike-slip shear zone/fault system developed at *c*. 550–540 Ma, and provided both the mechanism and opportunity for granite migration and ascent. Magma generated within the anatectic core migrated as dykes and buoyant diapirs through a ductile migmatite envelope and entered ductile extensional jogs within the mid-crustal shear zones (Fig. 3). Continuous displacement meant that zones of extension progressively became zones of compression, and vice versa, such that granite magma was forced through the ductile shear zones and, with the added impetus force of buoyancy, generally upward through the crust. Ductile movement within the mid-crust was accommodated at upper crustal levels by large scale fault systems situated directly above the zones of magma ascent. Extensional jogs within this system were filled as they formed by granite magma from below. Stoping and ballooning effects modified the granite contacts as the granites spread laterally during and after the magma was passively emplaced. Granite contacts alone therefore do not provide direct information concerning ascent and emplacement mechanisms. Moreover, the region illustrates how apparently post-tectonic intrusions in the upper crust occur contemporaneously with syn-tectonic magmatism in the mid-crust calling into question the usefulness of this terminology in using plutons to provide relative dates for tectonic events within unlike crustal levels.

The close temporal relationship between peak anatexis and regional strike-slip displacements merits further comment. We suggest that strike-slip deformation was initiated along zones within the mid-crust which had been thermally softened as a result of anatexis. Strike-slip deformation at *c.* 540 Ma need not, therefore, solely reflect external factors (e.g. outboard terrane accretion, change in subduction rate/vector etc.), but might be a consequence of progressive mechanical weakening of the crust during anatexis. Regional tectonics and granite generation may thus be inextricably linked processes, with granitic melts continuing to influence crustal behaviour during their ascent within actively deforming shear zone and fault systems. Therefore we find the collocation of granites and shear zones no surprise and predict that such relationships are common to granites within transpressional orogens, whether or not they have an intracrustal or mixed crust/mantle derivation. In many areas the shear zones/faults may be obscured by intrusions, while progressive strike-slip deformation may result in complete attenuation and closure of magma conduits, such that evidence for their prior existence may be cryptic in ancient orogens.

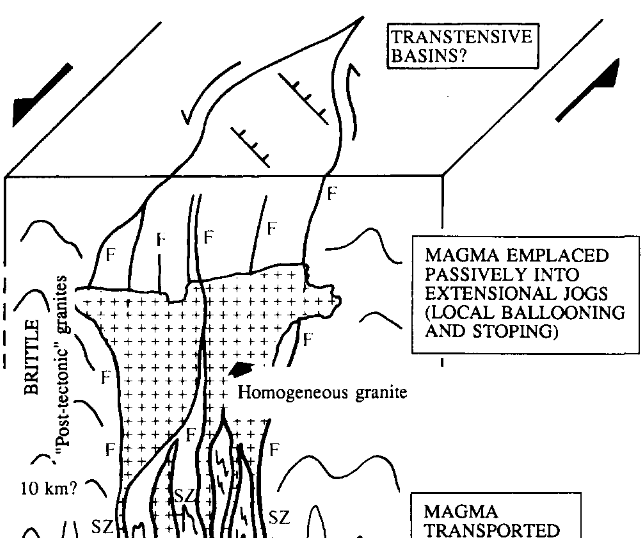

Fig. 3 Generalized model for the generation, ascent and emplacement of granite magma within mid- to upper crustal levels of a transpressional orogen (SZ, shear zone; F, fault).

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